# Isoscalar and Isovector Spin-M1 Strengths in $^{11}$B

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The M1 transition strengths provide important information on the nuclear structure because they could be a good measure to test theoretical nuclear models. Recently, the M1 transition strengths are of interest from a view of not only the nuclear physics but also neutrino astrophysics because the spin part of the M1 operator is identical with the relevant operators mediate neutrino induced reactions.

Raghavan *et al.* pointed out that the $^{11}$B nucleus can be used as a possible neutrino detector to investigate stellar processes [1]. High-energy neutrinos from the stellar processes like the proton-proton fusion chain in the sun and the supernova explosions excite low-lying states in $^{11}$B and $^{11}$C by M1 and Gamow-Teller (GT) transitions via the neutral-current (NC) and charged-current (CC) processes, respectively. Such neutrinos can be detected by measuring emitted electrons from the CC reaction and $\gamma$ rays from the de-excitations of the low-lying states. Since there is an isospin symmetrical relation between the $^{11}$B and $^{11}$C and both the NC and CC reactions can be measured simultaneously in one experimental setup, the systematic uncertainty in measuring a ratio of the electron-neutrino flux to the entire neutrino flux is expected to be small. Since the isospin of the ground state of $^{11}$B is $T = 1/2$, low-lying states in $^{11}$B are excited by both the isovector and isoscalar transitions. Therefore, both the isoscalar and isovector spin-M1 strengths are needed for estimating the CC and NC cross sections.

The cross sections of hadronic reactions provide a good measure for the weak interaction response since the relevant operators in the hadronic reactions are identical with those in $\beta$-decay and neutrino capture processes. Thus, we recently measured cross sections for the $^{11}$B($^3$He,$t$) and $^{11}$B($d$,$d'$) reactions to determine the isovector and isoscalar spin-M1 strengths in $^{11}$B.

The experiment was performed at Research Center for Nuclear Physics, Osaka University using 450-MeV $^3$He and 200-MeV deuteron beams. The measured cross sections were shown in Figs. 1 and 2. Since the ground state of $^{11}$B has non-zero spin, the cross sections for the $^{11}$B($^3$He,$t$) and $^{11}$B($d$,$d'$) reactions are described by an incoherent sum over the cross section of the different multipole contributions,

$$\frac{d\sigma}{d\Omega} = \sum_{\Delta J} \frac{d\sigma}{d\Omega}(\Delta J).$$

In order to determine the spin-M1 strengths, the cross section for each $\Delta J$ transition must be given to extract the $\Delta J = 1$ contribution.

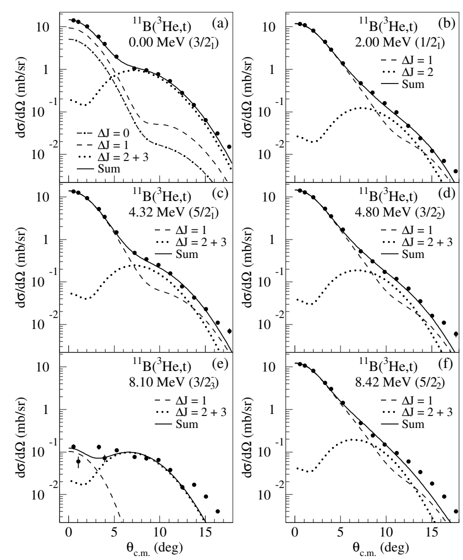


Figure 1. Cross sections for the $^{11}$B($^3$He,$t$) reactions compared with the DWIA calculation. The dash-dotted, dashed, and dotted curves show $\Delta J = 0$, $\Delta J = 1$ and $\Delta J \geq 2$ contributions, respectively. The solid curves are sums of the all multipole contributions.

For the $^{11}$B($^3$He,$t$) analysis, the cross section for the each $\Delta J$ transition was calculated by the distorted wave impulse approximation (DWIA) as seen in Fig. 1. Since the GT strength $B(\mathrm{GT})$ for the ground-state transition is known to be $0.345 \pm 0.008$ from the $\beta$-decay strength, the cross sections for the $\Delta J = 1$ transitions to the excited states in $^{11}$C can be related to the $B(\mathrm{GT})$ values by assuming the linear proportional relation. The obtained $B(\mathrm{GT})$ values are compared with the previous ($p$,$n$) result [2] in Table 1.

| $E_x$ (MeV) | $J^\pi$ | $B(\mathrm{GT})$ Present | $(p,n)$ |
|---|---|---|---|
| 0.00 | $3/2^-$ | $0.345 \pm 0.008$ | |
| 2.00 | $1/2^-$ | $0.402 \pm 0.031$ | $0.399 \pm 0.032$ |
| 4.32 | $5/2^-$ | $0.454 \pm 0.026$ | $0.961 \pm 0.060$ |
| 4.80 | $3/2^-$ | $0.480 \pm 0.031$ | |
| 8.10 | $3/2^-$ | $\leq 0.003$ | $0.444 \pm 0.010$ |
| 8.42 | $5/2^-$ | $0.406 \pm 0.038$ | |

Table 1. Measured $B(\mathrm{GT})$ values compared with the $(p,n)$ result [2].

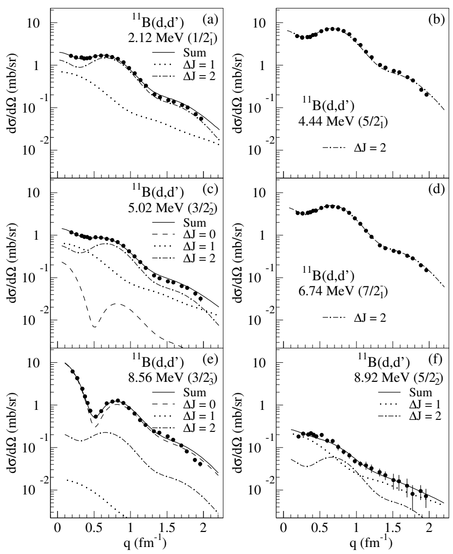


Figure 2. Cross sections for the $^{11}$B$(d,d')$ reactions. The dashed, dotted, and dash-dotted curves show $\Delta J = 0$, 1 and 2 contributions, respectively. The solid curves are sums of the all multipole contributions.

The present results are consistent with the $(p,n)$ result although several states are not separately resolved due to the poor energy resolution in the $(p,n)$ measurement. Assuming isospin symmetry is conserved, the GT strengths are easily related to the isovector spin-M1 strength $B(\sigma\tau_z)$,

$$\frac{B(\mathrm{GT})}{B(\sigma\tau_z)} = \frac{8\pi}{3}\frac{\langle T_i, T_{iz}, 1, \pm 1 | T_f, T_{fz}\rangle^2}{\langle T_i, T_{iz}, 1, 0 | T_f, T_{fz}\rangle^2}.$$

Although the isospin-symmetry breaking changes this ratio, the variation is usually small. Therefore, the GT strengths obtained from the charge exchange reaction are still useful to study the isovector spin-M1 strengths.

For the $^{11}$B$(d,d')$ analysis, the cross section for each $\Delta J$ transition was determined from the $^{12}$C$(d,d')$ reaction. Since the ground state of $^{12}$C has a zero spin, transitions to the discrete states in $^{12}$C are expected to be good references for the angular dependence of the cross sections for certain $\Delta J$ transitions. As shown in Fig. 2, the cross section for the $^{11}$B$(d,d')$ reaction was successfully decomposed into the each $\Delta J$ contributions. Although the 4.44-MeV $(5/2_1^-)$ state can be excited by both the $\Delta J^\pi = 1^+$ and $2^+$ transitions, the main part of the transition is due to $\Delta J^\pi = 2^+$. This result is explained by the fact that the

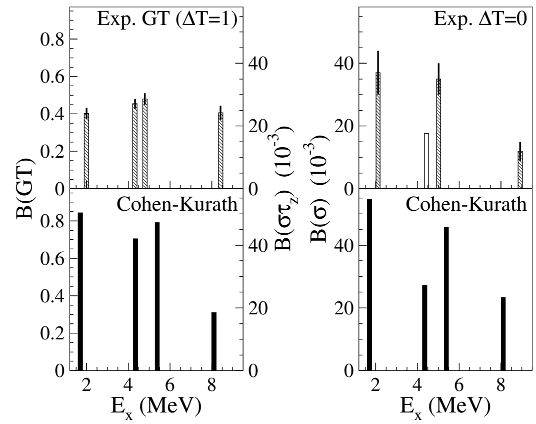


Figure 3. Measured $B(\mathrm{GT})$ $(B(\sigma\tau_z))$ and $B(\sigma)$ values are compared with the shell model predictions using the Cohen-Kurath wave functions [4]. The open bar in the right-upper panel shows the $B(\sigma)$ value for the 4.44-MeV state estimated from $B(\mathrm{GT})$ (see text).

strong coupling between the ground and 4.44-MeV states is expected since the 4.44-MeV state is considered to be a member of the ground-state rotational band. Since the observed $\Delta J^\pi = 2^+$ transition strength is much larger than the expected $\Delta J^\pi = 1^+$ strength, the $\Delta J^\pi = 1^+$ component of the transition strength can not be reliably extracted for the 4.44-MeV state. The transition strength for the 6.74-MeV $(7/2_1^-)$ state is also dominated by the $\Delta J^\pi = 2^+$ component, but the $\Delta J^\pi = 1$ transition to this state is not allowed. The isoscalar spin-M1 strength $B(\sigma)$ for the transition to the 2.12-MeV $(1/2_1^-)$ state is deduced to be $0.037 \pm 0.008$ from the $\gamma$-decay widths of the mirror states and the $B(\mathrm{GT})$ value [3]. Using this value, the cross section for the $\Delta J = 1$ transitions to the other excited states can be related to the $B(\sigma)$ values. Since the $\Delta J = 1$ cross section for the 4.44-MeV state was not reliably obtained in the $(d,d')$ analysis, the isoscalar spin-M1 strength was determined from the measured $B(\mathrm{GT})$ value and the relative strength of the isoscalar transition to the isovector transition calculated by using the Cohen-Kurath wave functions (CKWF) [4].

The obtained $B(\mathrm{GT})$ $(B(\sigma\tau_z))$ and $B(\sigma)$ values are compared with the shell model predictions using the CKWFs in Fig. 3. The CKWFs reasonably explain the experimental result except the quenching by a factor of 0.5-0.7. The present result will be useful in the measurement of the stellar neutrinos using the NC and CC reactions on $^{11}$B.

## References


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